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NPSHR (NPSH3) Improvement of a Low Pressure Safety Injection Pump

Frank Visser & Mark Ketelaar

Biography – Frank Visser

Frank Visser is Principal Engineer at Flowserve, Aftermarket Services & Solutions, in Etten-Leur, The Netherlands. He obtained a B.S. degree (Mechanical Engineering, 1985) from Technical College Alkmaar, The Netherlands, and a M.S. degree (Mechanical Engineering, 1991) and Ph.D. degree (Technical Sciences, 1996) from the University of Twente, The Netherlands. He has received the ASME 2017 Sankaraiyer Gopalakrishnan-Flowserve Pump Technology Award, is a member of the Industrial Advisory Board for the J.M. Burgerscentrum (JMBC), National Research School for Fluid Mechanics in the Netherlands, a former Associate Editor for ASME Journal of Fluids Engineering (two terms), and currently serves as Associate Editor for International Journal of Hydromechatronics and Journal of Applied Fluid Mechanics.

Biography – Mark Ketelaar

Mark Ketelaar is Senior Design Engineer at Flowserve, Aftermarket Services & Solutions, in Etten-Leur, The Netherlands. He obtained a B.S. degree (Mechanical Engineering, 2006) from Avans University of Applied Sciences, The Netherlands. He is involved in centrifugal pump design upgrades analyzed by computerized simulations. He worked in several Flowserve test laboratories and customer sites to verify theoretical study results with test data.

Short Abstract

This case study discusses the rerate of a set of vertically-mounted single-stage end-suction centrifugal pumps used for low pressure safety injection (LPSI) in a nuclear power plant. The original LPSI pumps were supplied early 1970's and for safety purposes it was decided to overhaul these pumps to improve NPSHR (i.e. NPSH3).

The rerate consisted of replacing the existing impeller with a new design yielding close to identical head performance characteristic, yet lower NPSHR. Aim was to improve NPSHR by (minimally) 0.5 m (1.64 ft) at rated capacity of 682 m^3/h (3003 USGPM) and 1470 r/min running speed, and demonstrate by test the actual improvement in NPSHR

Contents

- Particulars
- Design Objectives
- CFD Study
- Experimental Testing
- Results
- Concluding Remarks

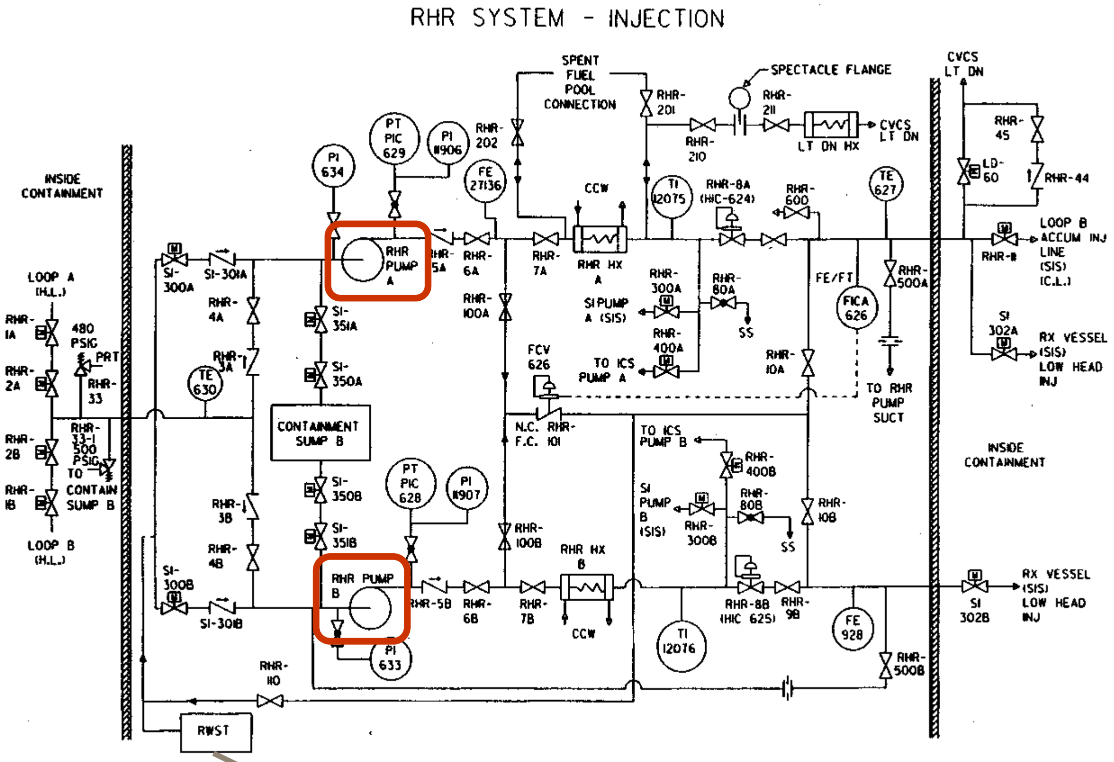
Particulars

- Re-assessment of Low Head Safety Injection (LHSI) pumps at a nuclear power plant (➔ safety improvement)
- LHSI pumps are part of the Emergency Core Cooling System (ECCS), and they serve to:
  - ➢ Inject water from the refueling water storage tank into the reactor coolant system during large breaks
  - ➢ Provide makeup water for Residual Heat Removal (RHR)

Particulars

- RHR System:

- LHSI (RHR) Pumps



Refueling Water Storage Tank

Particulars

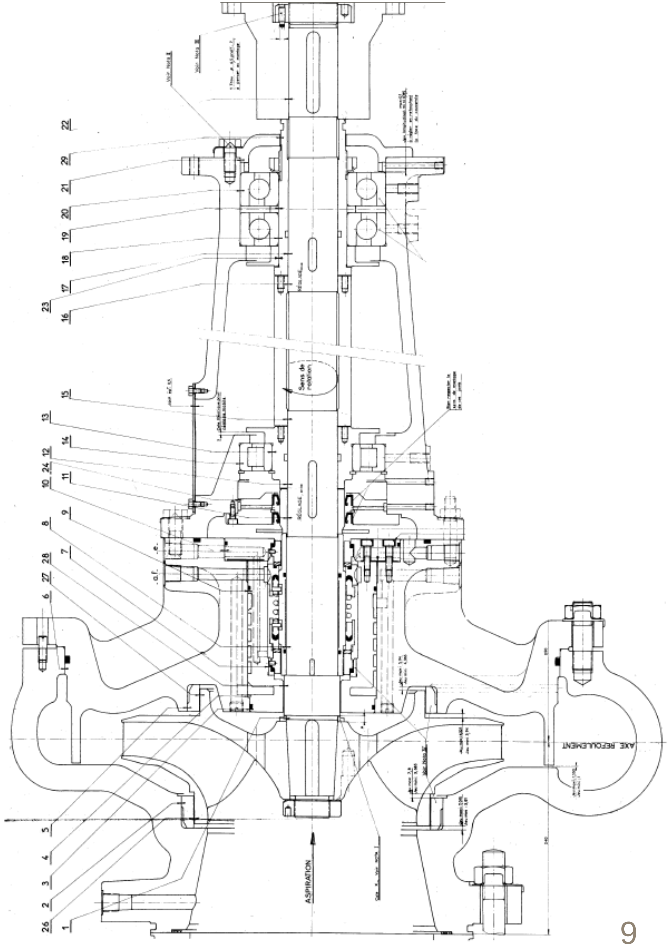
- During long term core cooling, RHR recirculation mode debris (from the containment sump) could partially clog the sump filter lowering the NPSHA for the LSHI pumps

- This necessitated an impeller upgrade to improve NPSHR (NPSH3)

Particulars

- **LHSI Pump**
  - Single stage
  - Single suction
  - Overhung design
  - Vertically installed
- **COS** (existing)
  - Speed = 1470 RPM
  - Capacity = 682 m³/h (3003 USGPM)
  - Head = 69 m (226.4 FT)
  - NPSHR = 4.5 m (14.8 FT)
  - NPSHA = 4.6 m (15.1 FT)

➔ F_{NPSH3} = 1.02!



Design Objectives

- **NPSH**
  - ❖ Improve NPSH3 margin (F_{NPSH3})
    - ➢ Lower NPSH3 ≥ 0.5 m @ 682 m^3/h (1470 r/min)

      ➔ $F_{NPSH3} \geq 1.15$*
  - ❖ This desired NPSH3 improvement translates to a design suction specific speed of Nss ≥ 11,700 (USCU)

*Note: U_{eye} = 20 m/s, indicating higher recommended margin (F_{NPSH3} ≥ 1.3), but for this case not feasible

[Ref. J.F. Gülich, *Centrifugal Pumps*, Springer, 2010]

Design Objectives

- **QH**
  - ➢ Rated head:

    69 m @ 682 m^3/h (226.4 FT @ 3003 USGPM)
  - ➢ Stable operating window: 12% – 132% Q_{rated}

    80 – 900 m^3/h (352 – 3963 USGPM)
  - ➢ Maximum flow head requirement:

    61 m @ 900 m^3/h (200 FT @ 3963 USGPM)
  - ➢ New QH curve within –0% / +7% of old QH

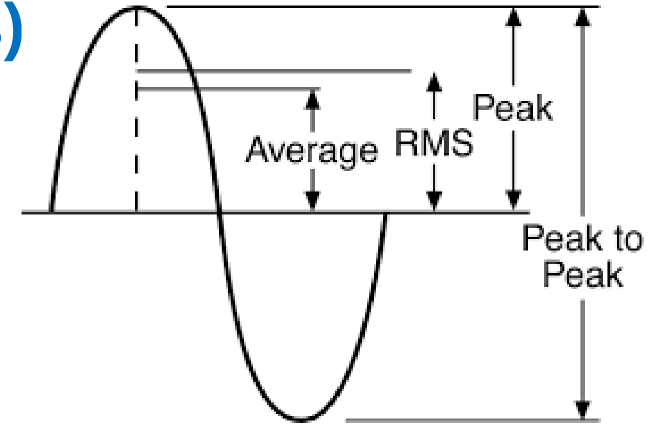
Design Objectives – Acceptance Criteria

- **Vibration** (bearing housing)
  - **VDI 2056:1964** (ISO 2372:1974)
    - 80 – 300 m^3/h: **4.5** mm/s (0.18 in/s) RMS
    - 300 – 900 m^3/h: **2.8** mm/s (0.11 in/s) RMS

Vibration behavior	Group K	Group M	Group G	Group T
Good	0.71	1.12	1.8	2.8
Usable	1.8	2.8	4.5	7.1
Still admissible	4.5	7.1	11.2	18
Inadmissible	> 4.5	> 7.1	> 11.2	> 18

Design Objectives – Acceptance Criteria

- **Pressure pulsations (@ flanges)**
  - ➢ Suction and discharge pulsations less than 3% peak
- **Capacity fluctuations**
  - ➢ Less than 3% peak



Provided that benchmark test (original pump) meets these criteria; otherwise benchmark test is determinative

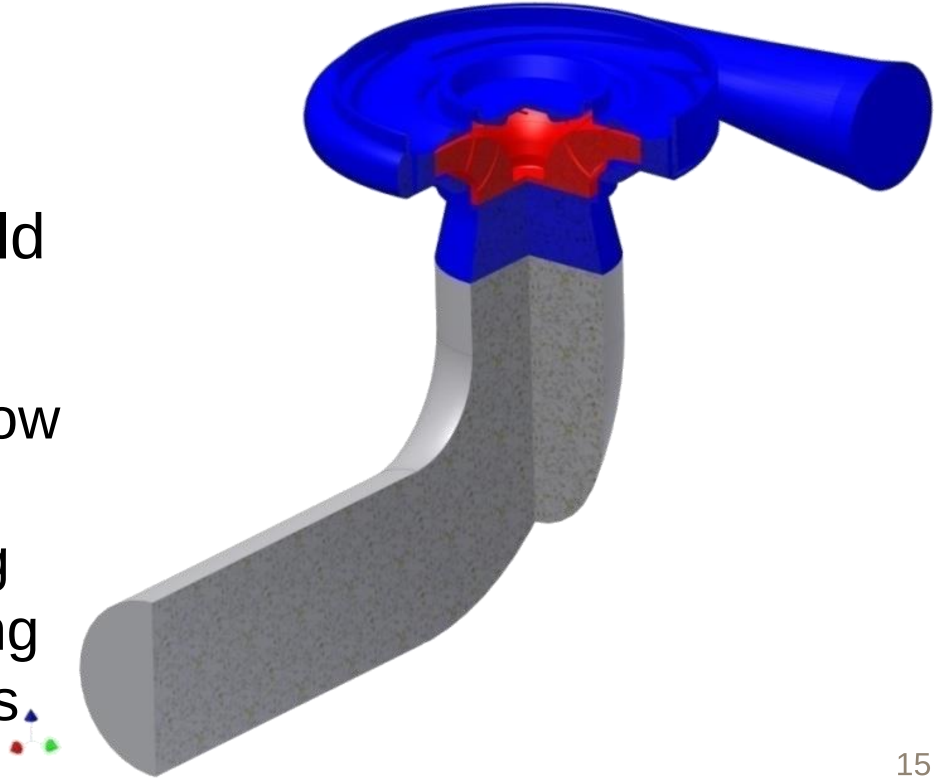
CFD Study

- The CFD study assisted in:
  - ➢ Benchmarking hydraulic performance of the existing design (prior to testing)
  - ➢ Evaluating new (impeller) design iterations
- Basis for new design was selected from database of existing impeller hydraulics with known performance (12,000 Nss)
- Existing pump waterways were modelled from 3D geometry scan
- New impeller designs were modelled directly in 3D CAD

CFD Study

3D CAD Model

- **Impeller**
- **Casing**
- **Suction elbow** (field configuration)

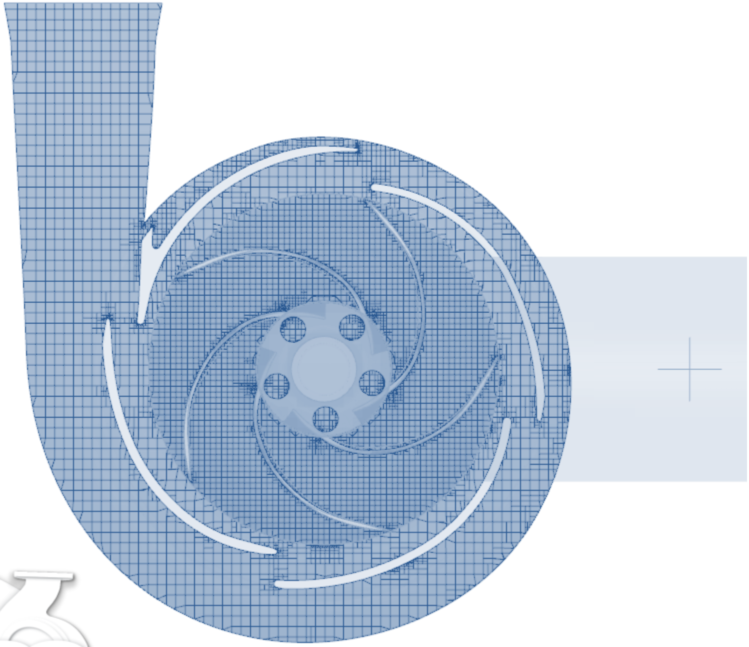


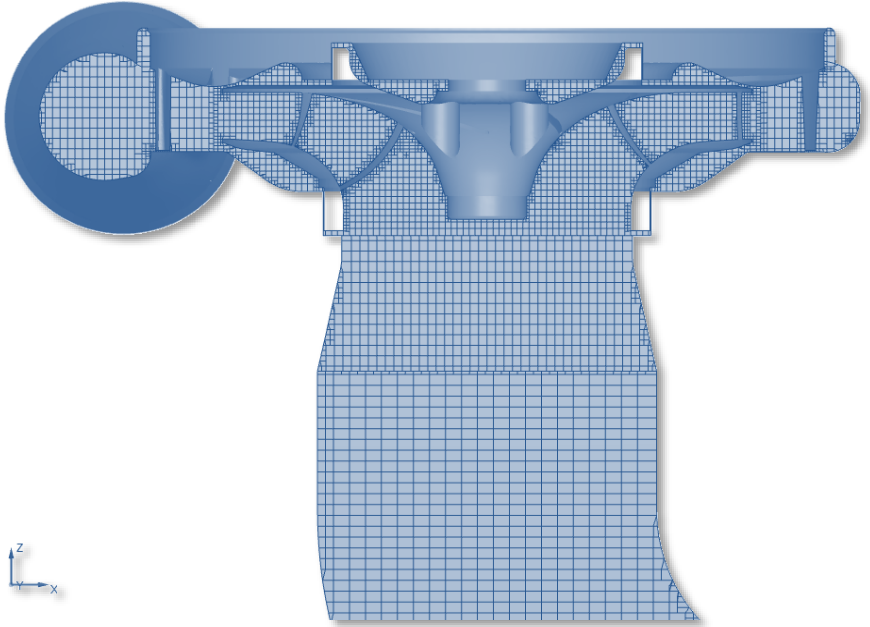
Model includes all internal flow (leakage) paths:

- Impeller eye wear ring
- Impeller back wear ring
- Impeller balance holes

CFD Study

Computational Grid

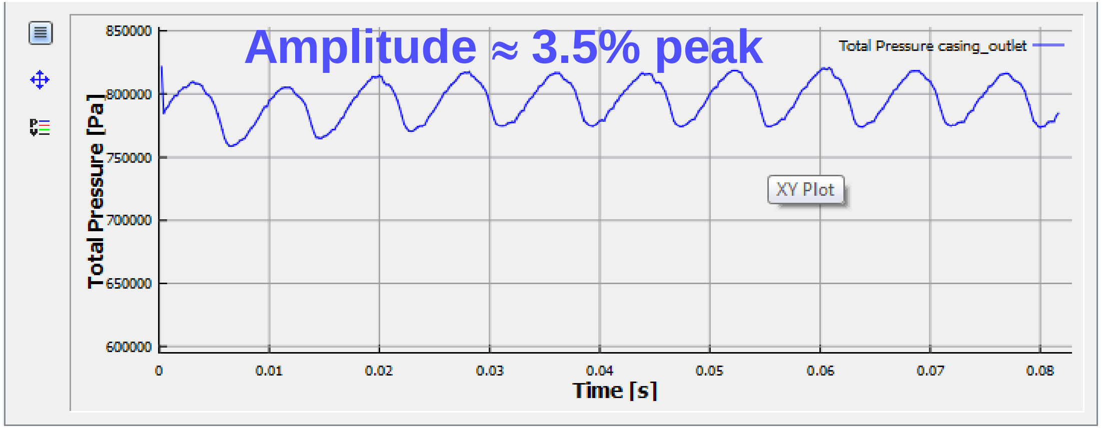


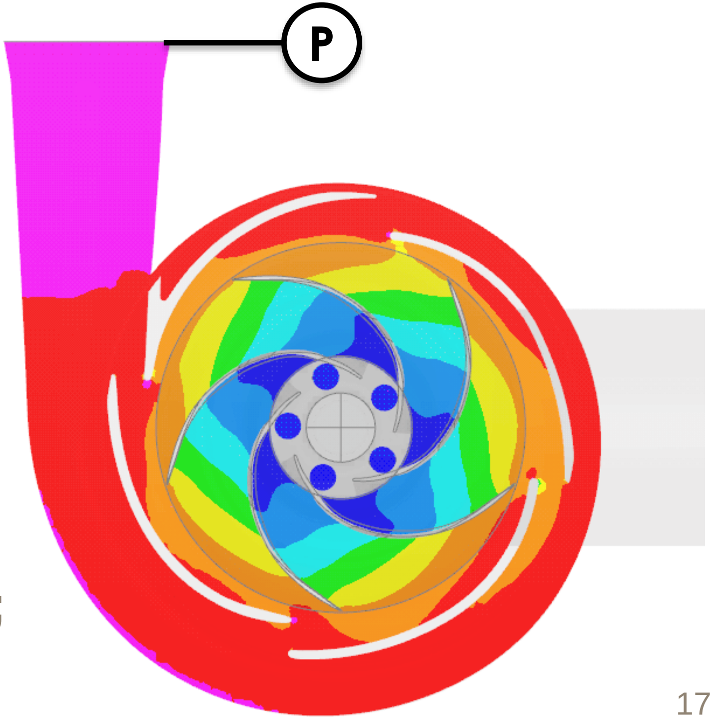


(Binary Tree Mesh)

CFD Study – Outcome

CFD Simulated Pressure Pulsation (transient simulation)





Existing impeller @ rated capacity; $P_{total, inlet}$: 1.0 bar(abs)

CFD Study – Outcome

▲ Benchmark Test Data (TDH)

CFD:

▪ TDH existing

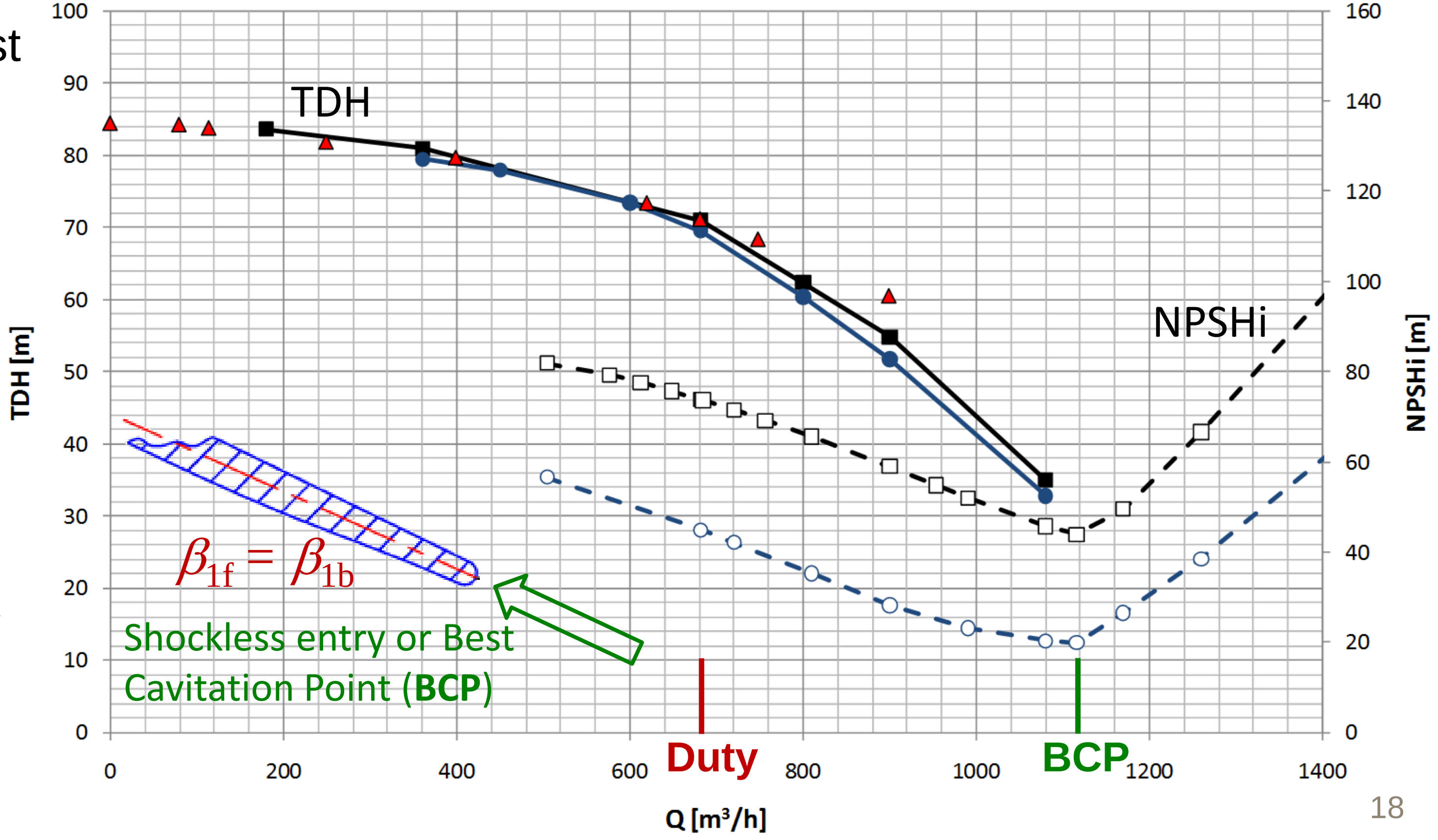
• TDH new

❑ NPSHi existing

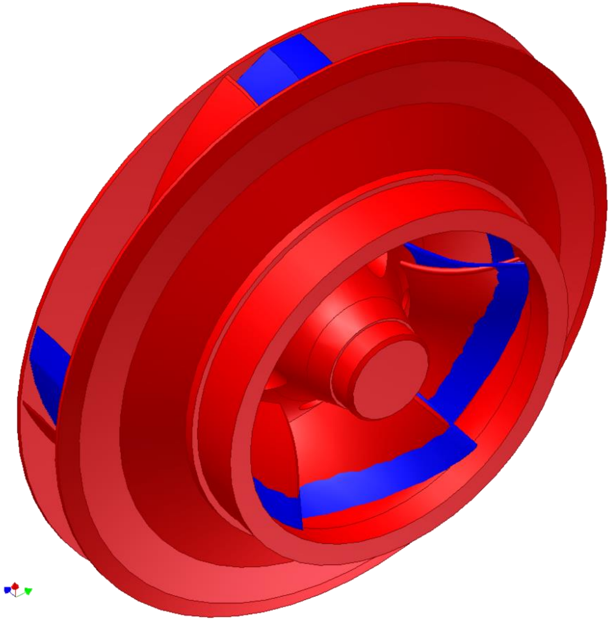
○ NSPHi new

Q_{duty} @ 60 % BCP

BCP @ same flow for both designs

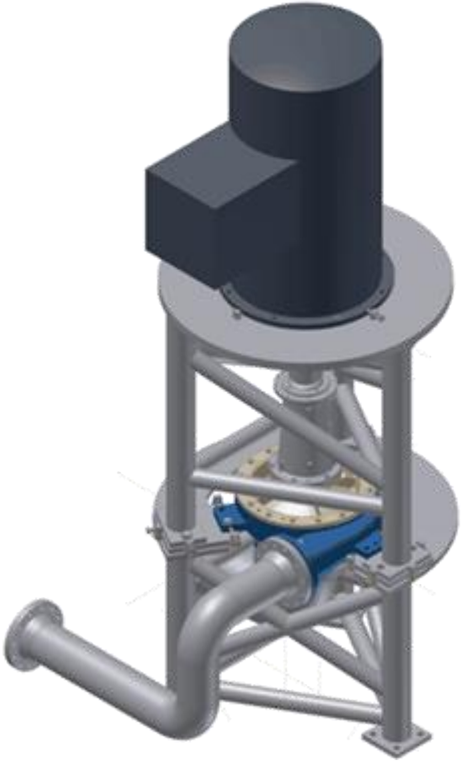


CFD Study – Outcome

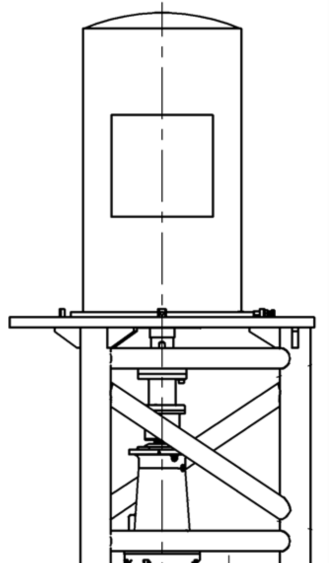


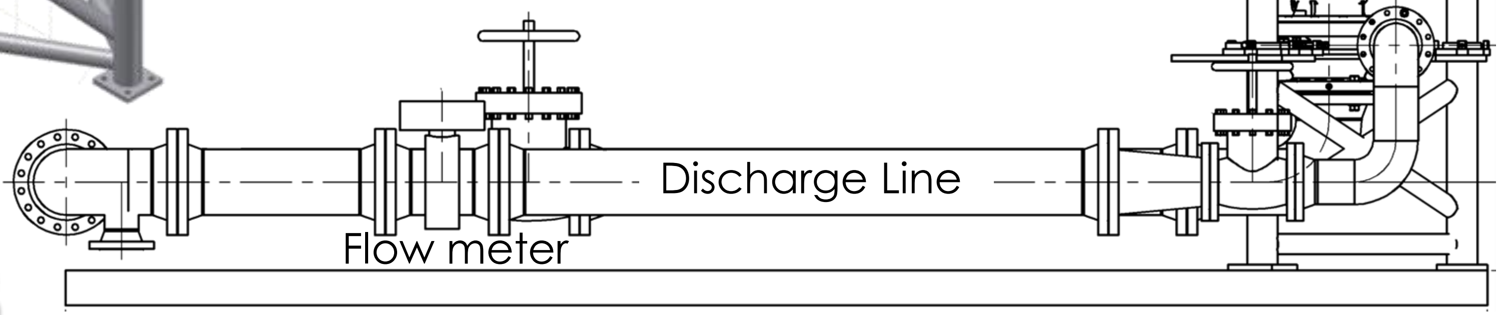
- TDH from CFD compares well with benchmark test, but shows under prediction at high flows (-9% @ 900 m^3/h)
- Incipient cavitation NPSH of new design is much better, indicating that lower NPSH3 can be expected for the new impeller
- Actual performance (including pulsation measurements) to be determined from testing of (rapid) prototype impeller

Experimental Testing



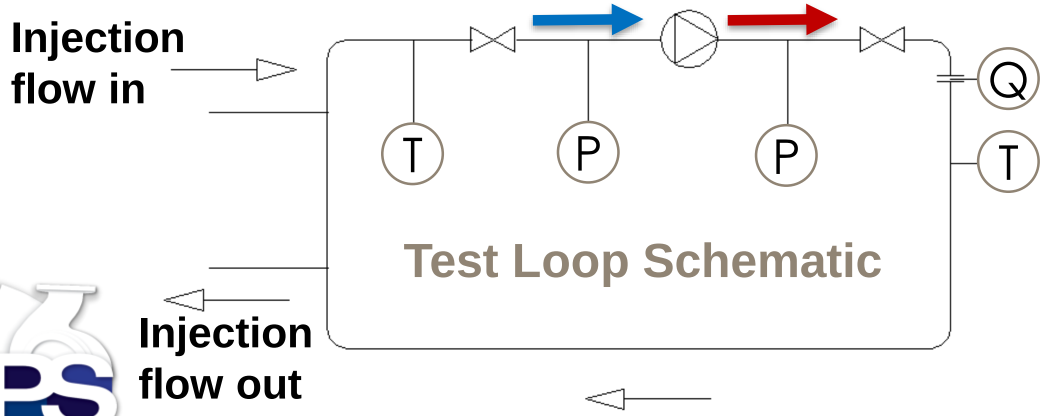
- **Instrumentation**
  - Electromagnetic flow meter
  - Tachometer (speed pickup)
  - Calibrated test motor (power)
  - Pressure transducers





Experimental Testing

- Temperature controlled test loop with injection cooling
- Performance testing in compliance with Hydraulic Institute
  - ANSI/HI 14.6-2016



Experimental Testing

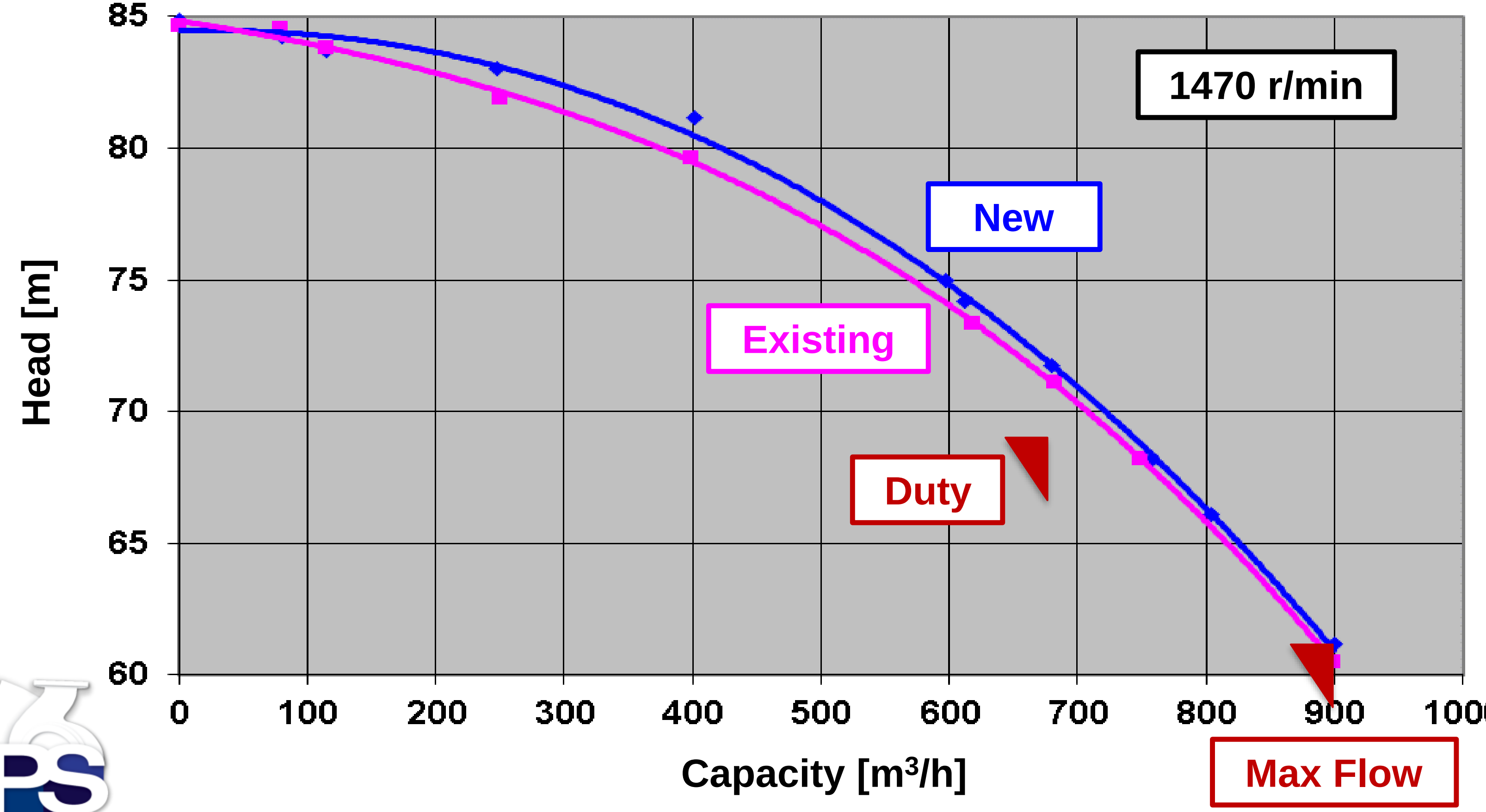
Impellers Tested*

- Original impeller
- Original impeller with **plugged balance holes**
- New impeller
  - ➢ Initial new design
  - ➢ Design modifications

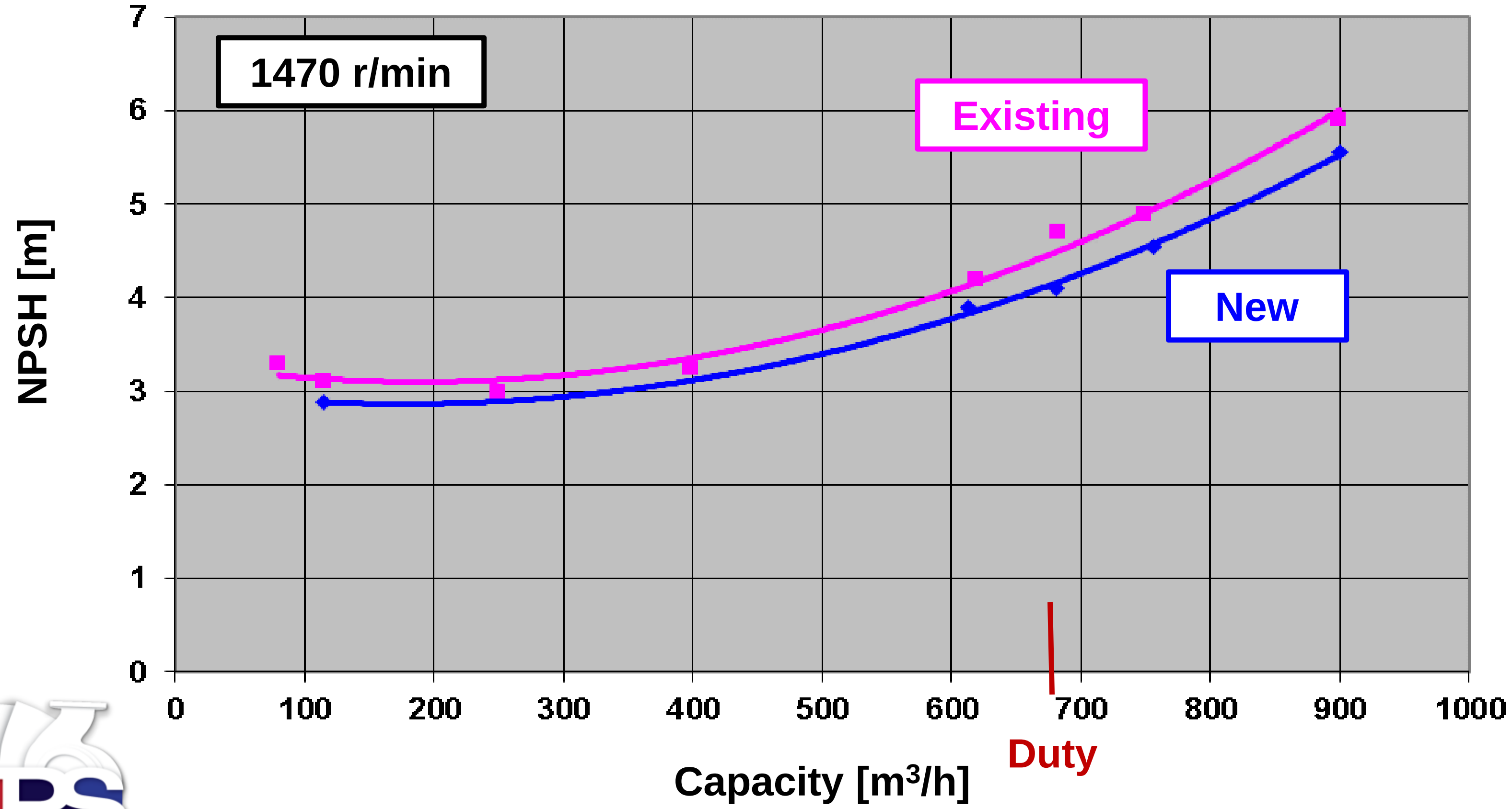
This showed only a minor reduction in NPSH3 (0.2 m)

***Prior to each test a vacuum test was conducted on pump and test loop to check sealing of gaskets**

Results – Head Characteristic



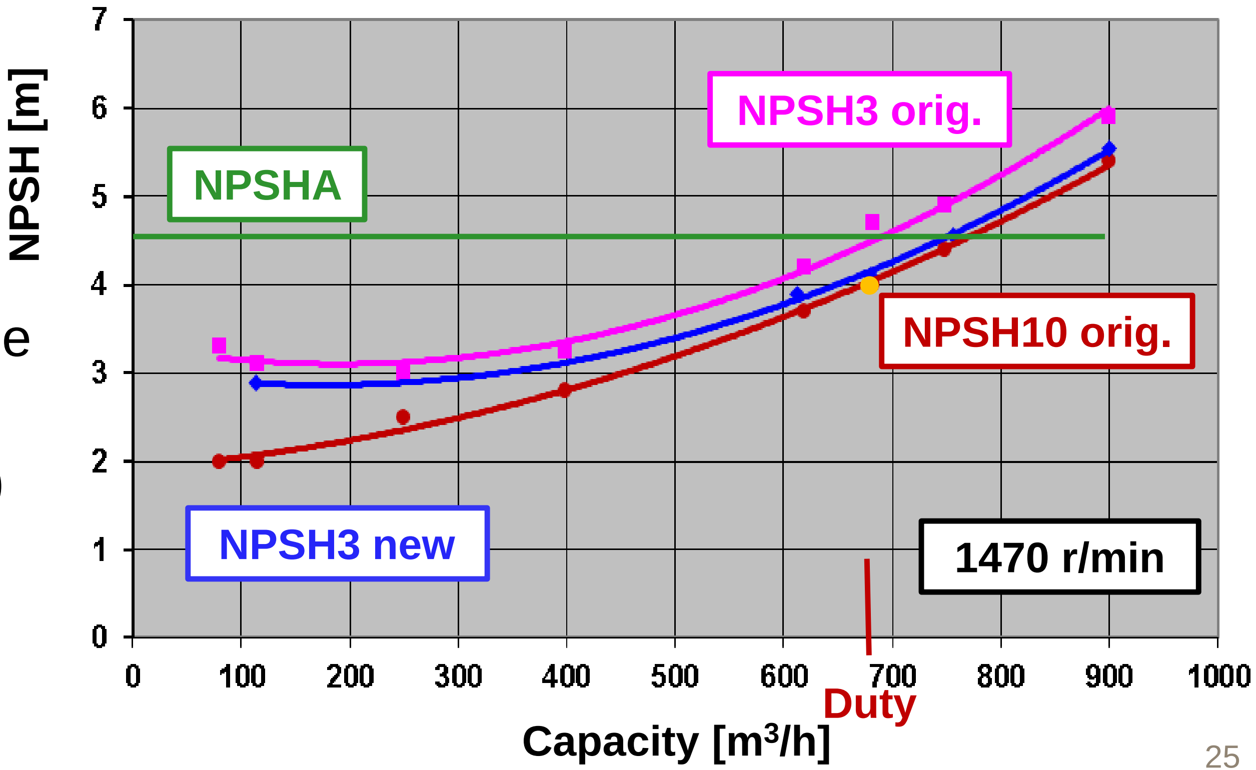
Results – NPSH3



Results – NPSH10

Special test

- **NPSH10**
- **Original impeller**
- Safety measure pending the upgrade (customer request)
- Marking the limit (●) of negative NPSH3 margin ($F_{NPSH3} < 1$)



Concluding Remarks

- New impeller developed by design iterations, starting from existing reference hydraulic
- CFD was used to map hydraulic performance of existing impeller and new design
- Final design was manufactured by rapid prototyping and actual improvement in NPSHR(NPSH3) was demonstrated by test (Existing vs. New)
- Plugging impeller balance holes showed little improvement in NPSH3

Nomenclature

BCP	=	Best Cavitation Point
BEP	=	Best Efficiency Point
CFD	=	Computational Fluid Dynamics
ECCS	=	Emergency Core Cooling System
F_{NPSH3}	=	NPSHA / NPSH3
LHSI	=	Low Head Safety Injection
LPSI	=	Low Pressure Safety Injection
NPSH	=	Net Positive Suction Head
NPSHA	=	NPSH Available
NPSHR	=	NPSH Required
NPSH3	=	NPSH for 3% Head Drop
NPSH10	=	NPSH for 10% Head Drop
Nss	=	Suction Specific Speed
RHR	=	Residual Heat Removal
TDH	=	Total Differential Head
U_{eye}	=	Impeller Eye Peripheral Velocity

Thank you for your attention

Questions?